Conductor Protection Considerations
And ANSI Standard C2

Charles Pratt, P.E.
Quadrelec Engineering Corp.
918-488-8879

ABSTRACT

The National Electrical Safety Code, ANSI C2, levies general requirements for the protection of underground electrical conductors within a distribution system. Specifically, the standard requires conductors, jacketing, and shielding to be properly protected so that cables will not be damaged, except at the location of a fault.

The requirements of this standard impact both the type and location of protective devices used for the protection of cables. Many times standard non-current limiting fuses are used to protect shielded underground primary voltage cables. Low voltage service cables are protected solely by the primary fuses of the distribution transformer. Both of these situations result in compliance issues. Compliance problems are aggravated by the shielding designs of medium voltage cables and the low driving voltages available on 240/120 V and 208Y/120 V systems.

Using an actual case history for a line-to-neutral fault in a residential underground system, this paper explores the difficulties in complying with the NESC requirements in low voltage systems. It analyzes design practices in this particular area of the NESC rules. The limitations of common devices, such as fuses, and common design practices used to meet the NESC requirements for protection of medium voltage cables are also analyzed.

INTRODUCTION

The National Electric Safety Code (NESC), ANSI C2-1997, Rule 330D requires that underground cables be designed to withstand the effects of a fault both in magnitude and duration, except in the immediate vicinity of the fault. This requirement not only applies for the conductor, but also for the insulation and shielding. It will be demonstrated within this paper that adherence to this rule is not easily accomplished with standard overcurrent protective devices such as circuit breakers and fuses.

In order to demonstrate the problems associated with compliance with this rule, an example is presented from the author’s experience.

NESC DISCUSSION

The NESC rule 330D reads as follows:

> "D. The conductor, insulation, and shielding shall be designed to <u>withstand the effects</u> (Emphasis added) of the expected magnitude and duration of the fault current, except at the immediate vicinity of the fault."

Interpretation and application of this rule is not as straight forward as one might think, and unfortunately little guidance is provided within the NESC, or within handbooks written on the subject. The phrase "withstand the effects" is ambiguous and open to interpretation.

It is typical within other IEEE standards, such as Std 242, to interpret cable "withstand" as that recommended by IPCEA standards. Neither the IEEE or IPCEA standards are referenced within the NESC. These standards limit current magnitudes for a duration of less than 10 seconds to the short circuit rating of the insulation and for longer duration of time up to the continuous rated temperature of the insulation. For example, conductors insulated with 75 deg. C thermoplastic insulation are usually limited to a short time heating of 10 seconds or less, to 200 deg. C. Any other conductor or shielding material within or next to the conductor is also limited to the same maximum short and long time temperatures.

Short circuit protection of conductor insulation within IEEE and IPCEA standards can be accomplished quite easily over all ranges of faults with current limiting fuses. This is true as long as the rating of the fuse either matches the continuous ampacity of the conductor or does not exceed three times the rated ampacity. If circuit breakers are substituted, it is quite possible that the conductor can be left with little or no short circuit protection for high magnitude faults.

To demonstrate this principle Figure 1 is presented. Secondary cable protection will be addressed first. Figure 1 displays the IPCEA withstand curve for 4/0 thermoplastic insulated cable.

This figure also shows the characteristic curves for a current limiting fuse (FU1), a non-current limiting fuse (FU2), a non-current limiting fuse (FU3) and a molded case breaker. In each case the protective device is rated at 225 A except for FU3. FU3 is set at approximately three times the ampacity of the cable.

From Figure 1, one can easily see that fuses FU1 and FU2 protect the conductor over any range of fault condition. In all cases, the fuse curve is to the left of the conductor damage curve. Fuse FU3 only provides short circuit protection. For the molded case breaker, however, the breaker curve and the conductor withstand curve could overlap where currents are greater than approximately 110 kA.

Therefore, for currents greater than 110 kA the NESC criteria for conductor protection would be violated with a molded case breaker. In a realistic example, using a single-phase distribution transformer, such high levels of current would not be achievable. Assuming that the secondary conductors are rated for the full load rating of the transformer, a 50-kVA transformer with an impedance of 0.18 percent would be required. Such a transformer is not commercially available. Any motor contributions in this analysis have been ignored because the effect of their inclusion is negligible.

Applying this situation to the more general case of secondary conductors rated for the full load capability of the transformer and protected by fuses or breakers the following analysis might be made.

Using Figure 1 it can be deduced that, as long as fault currents do not exceed 488 puA (per unit amperes) of the conductor full load rating, standard protective devices will be adequate. It could also be deduced that, where the conductor rating matches the transformer rating and the transformer impedance does not approach 0.2 percent, all would be well. This will be the situation most if not all of the time.

The other problem to be analyzed is protection of the shielding of medium voltage cables to comply with the NESC.

fig 1

Fig 2

Medium voltage cables available within the industry usually have shielding which can consist of copper or aluminum metal tape or a semi-conductive plastic with drain wire construction. In this analysis the easiest shielding construction to protect, an MV cable with a 5 mil copper tape overlapped 12%, will be considered. According to literature from one cable manufacturer this shield type, on a 133% insulated #1 AWG EPR cable, would have a one second withstand rating of 780 amps. This is approximately the same short time rating as a #9 AWG PVCconductor.

Figure 2 is presented to show the conditions when standard fusing practice is used. The situation depicted is considered very typical of most of the underground riser to pad-mount transformer arrangements. The shield tape withstand curve is represented with a #9 PVC conductor driven to the maximum allowable temperature rise for PVC.Referring to Figure 2 the following characteristics are plotted.

The insulation damage curve for the MV90 cable, assuming all current flow is over the main conductor. (3)

A 140-amp T fuse commonly used to protect this cable at a riser pole. (7)

An 80-amp T fuse. (6)

An 80-amp K fuse. (5)

The withstand of the metal tape shield. (4)

Last the characteristics of a 167-kVA transformer primary fuse. (2)

Looking at Figure 2, one will notice that the cable itself is adequately protected by the 140-A riser pole fuse. This same 140-A fuse provides no protection for the shield conductor. This assumes all current flows over the shield tape. Until the shielding fuses, it will carry most of the fault current. The 80-A, K type, fuse protects the shield against some damage. For comparison purposes the effects of using an 80 A, T-type, fuse is also shown. From this graph one can see that compliance with the NESC would require fusing the cable at lower than rated ampacity. Using a smaller fuse would not be a problem because it would still coordinate with the primary fuse of the transformer. If loading of the underground feeder is near the maximum, use of the 140-A fuse might be required. In that case, protection of the shield would be a problem.

In actual practice, this cable runs in ductbanks along with a system neutral or primary system equipment ground conductor. The effect of the neutral or ground conductor would be that of shunting a portion of the fault current away from the shield tape. Figure 3 shows the effect when only 33% of the fault current flows through the shield, the rest flowing over the neutral conductor. The curves of the conductor withstands have been increased by a factor of 3 to demonstrate the effect. It can be seen that the fuse now adequately protects the shield. Assuming that this much current will be diverted away from the shield to the neutral would be inappropriate. More research is needed to determine the actual amount of current that will flow over the shield. This is very complex and a function of shield constructions and neutral conductor impedances. The safest approach would be to assume that the neutral provides no effective shunting effect for fault current.

This analysis has not raised any unresolvable red flags of concern yet. Secondary cables can be adequately protected with fuses set for the ampacity of the cable. Primary cable protection becomes more difficult when trying to achieve protective device coordination and at the same time meet NESC requirements.

What happens if the conductors are not directly protected by fuses on the secondary side of the transformer but instead rely upon the fuse protection on the transformer primary? As will be noted in subsequent paragraphs, this presents a totally different problem for conductor protection.

DESIGN PRACTICES

It has been the author’s experience within the utility, industry, and government sectors that the most common protective device used for the protection of low voltage cables is the primary fuse of the transformer. When service conductors are fed from the secondary of a distribution transformer, fuses or

Fig 3

other protective devices such as cable limiters are rarely installed at the secondary lugs of the transformer. This practice is allowed within the NESC. The NEC (NFPA 70) requires conductors to be provided with both overload and short circuit protection. Within NFPA 70 (NEC), the practice of secondary conductor protection from primary transformer fuses would only be allowed where the transformer is a single-phase two wire secondary transformer. With a single-phase two wire secondary transformer, the primary current will always be a direct ratio of the secondary current under all situations. If the transformer is a single-phase three-wire transformer, such as a typical 240/120 volt distribution unit, the primary current during a line-to-neutral overload or fault will only be one-half of the value of a line-to-line fault. Therefore, even if the primary transformer fuse has a rating equal to the transformer full load primary amperes, secondary conductors selected for the secondary full load amperes will be left with no overload protection.

The situation of primary protection only is shown in Figure 4. The conductors in this figure have been selected at the full-load rating of the transformer. Note that the conductors are provided short circuit protection for both line-line and line-neutral faults. The NESC allows much more latitude in conductor protection. If one looks and Section 16, Rules 160 and 161, they will notice that conductors can be provided overcurrent protection in many ways. Specifically, we can use fuses, breakers, protective relaying, or remote alarms. These devices must protect the conductors against “excessive heating.” Again, a designer or a utility company must determine what it considers as excessive heating. In a case where diversified residential loads have been used to size the transformers and service laterals, the possibility of a line-to-neutral overload on a transformer is extremely remote. An additional factor minimizing the chance of overload is that conductors also have an emergency ampacity higher than that of the normal continuous ampacity

Operation of the conductors at the emergency ampacity, if it does not exceed more than 100 hrs per year, will not significantly reduce cable life. For example, a conductor with an insulation rating of 90 deg. C continuous will have an emergency overload temperature rating of 130 deg. C.

Fig 4

Using equations from IEEE Std 242, Chapter 11, one would find that this correlates to a 25 percent overload on the conductor.

A case history example from the author’s experience will be used to demonstrate what can happen when a designer of a residential underground secondary system violates the design previously discussed. Namely that the secondary conductors are rated for the full-load rating of the transformer.

CASE HISTORY

In 1995, the author was called upon to investigate a fire within some recently renovated family housing units at Ft. Sill Oklahoma. Renovation of the interiors of the housing units had just been completed. Renovation included a complete rewiring of the interiors of the units. Simultaneously another contract was in progress to replace the overhead primary and secondary distribution systems feeding the housing units with a new underground distribution system. A fire began at one of the units when an electrical contractor energized an underground service feeding four family housing units. Immediately upon energization of the conductors, occupants of the housing units noticed smoke and arcing taking place interior to the dwellings. After exiting the dwellings, some occupants noticed smoke rising from the underground secondary cable service pedestals located in the alleys behind the units. Only moderate property damage occurred. No deaths or injuries were reported.

The primary fuses for the pad-mounted transformers did not operate to clear the fault over a period estimated at 20 minutes after the fault occurred. The fault was cleared by manually de-energizing the underground primary lateral to the transformer. Prior to power disconnection, high levels of currents flowed over phase, neutral, and grounding conductors resulting in extreme damage to the underground service conductors. Stray currents circulating through interior wiring systems, piping systems, and metal siding of the housing units caused damage to branch circuit wiring. The same currents came very close to igniting wood structural members under the metal siding. Small appliance damage was confined to the melting of cords to grounded appliances such as refrigerators with icemakers.

The investigation was directed to:

- Determine why protective devices did not function to clear the fault

- Assist in the visual inspection of the damage to determine the extent of damage

- Determine any deficiencies requiring correction to preclude recurrence of the problem

SYSTEM DESCRIPTION

The four affected housing units and the physical layout of the electrical system is shown in Sheet 1. A single-phase 7.62 kV underground line fed pad-mounted transformers located within an alleyway behind the four affected housing units. The underground primary has not been shown in the drawing. Transformers are single-phase 7620-240/120 volt units. The 75-kVA transformer involved in the fault had a percent impedance voltage of 2.5%. Underground primary cable serving the transformers was #1 AWG 15-kV cable with a 100% rated concentric neutral. Secondary service lateral conductors ran from the transformer to the service pedestals “P1” and “P2.” Service drop conductors ran from the service pedestals to the service entrance disconnect switch on the outside of each housing unit. All underground service conductors were 1/0 AWG in size. Although not required by code a #6 AWG insulated grounding conductor was installed in each service lateral and service drop. The #6 AWG conductor was bonded to the service neutrals at each housing unit, at a ground lug in each service pedestal, and at the pad-mounted transformer grounding system.

The only protection provided for the underground secondary cables was provided by the primary fuses on the transformer. No secondary fuses or cable limiters were installed at the secondary lugs of the transformer. The primary transformer fuses were of the current limiting drawout bayonet type.

A fault occurred when the electrical contractor energized the new underground services to the four affected housing units. At that time, the units were also being fed from the existing overhead distribution system. As it turned out, the phase and neutral conductors between pedestals “P1” and “P2” were reversed at one end.

Sheet 1

Sheet 2

This resulted in a bolted line-to-neutral/ground fault condition within the secondary service system. A diagram of the system during the fault and the resulting computed current flow throughout the system is shown in Sheet 2.

BASIC ANALYSIS

The conductor sizes, lengths, calculated currents, and resulting damage from the diagram on Sheet 2 are noted in Table 1.

Table 1

Conductor Label	Size [AWG]	Length [ft]	Fault Current	Damage
BJ	#6	1	600 A	Burned clear during fault
G1	#6	40	600 A	No visible heat stress damage. Current dropped to a negligible amount after “BJ” fused.
G2	#6	58	256-750A	Insulation charred
G3	#6	95	750-856 A	Insulation charred
G4	#6	78	750-856 A	Insulation charred
G5	#6	81	0 A	No damage, conductor not terminated during fault
G6	#6		<<250 A	No visible heat stress damage
H1	1/0	40	750-856 A	No visible heat stress damage
N1	1/0	40	256-750A	No visible heat stress damage
N2	1/0	58	256-750A	No visible heat stress damage
N3	1/0	95	750-856 A	No visible heat stress damage
N4	1/0	78	750-856 A	No visible heat stress damage
N5	1/0	81	<<250 A	No visible heat stress damage
Conductor Label	Size [AWG]	Length [ft]	Fault Current	Damage
PN	#2		<<250 A	No visible heat stress damage

During the faulted condition, fairly high levels of current flowed through the equipment grounding system and neutral conductors. Stray currents also flowed over interior metallic paths interconnected with the electrical grounding system. The bonding jumper “BJ” was fused and separated approximately 6 inches from the transformer ground lug. Considering the calculated results of this study, it can only be deduced that this jumper fused due to one or more of the conductor strands being cut or damaged. This conclusion results from the fact that (1) this bonding jumper carried virtually the same current as other conductors of the same size which showed no distress and (2) the conductor showed no signs of overheating 2 inches to either side of the fused location.

While current was not computed for PN, N5, G6, N6 and N7, it is known that the magnitude and duration of the current was high enough to heat a #12 AWG conductor to the melting point of the plastic jacket on the interior NMC cable. This fact was substantiated by the damage to several branch circuits within housing unit 1141-A.

In this particular situation, the damage was aggravated by two design-related issues. The system designer sized the secondary service lateral conductors based upon expected demands. The transformer was sized for additional load growth resulting in the ampacity of the secondary conductors not matching the full load rating of the transformer.

The situation in terms of the protective device, the primary transformer fuse, is shown in Figure 5. Note the relationship of the primary fuse curve to the secondary conductor damage curves. The computed line-neutral initial fault current flowing during the actual conditions is shown as a vertical line. Also depicted are maximum available fault current levels at the secondary terminals of the transformer. From Figure 5, one can illustrate that the secondary conductors are not protected below fault current levels of 3,000-A.

Fig 5

General Case Analysis:

In order to derive general lessons from the very specific preceding example some assumptions will need to be made. After making these assumptions some general observations will be introduced.

Given the following situation:

Single-phase 240/120 V secondary transformer

Primary fuse of transformer sized no greater than 1.25 times the full-load rating.

Type K fuses will be used due to restricting the analysis to overhead transformers.

Minimum available transformer impedance 1.2 percent.

Fuse must protect cable only for times less than 10 seconds. Times longer than this are affected by pre-fault loading, ambient temperatures, and other variables.

The smallest secondary conductor normally used is #6 AWG.

Line-neutral connected primaries result in larger fuse sizes for a given size of single-phase transformer. Therefore, line-line connected transformers are not included in analysis.

Using these constraints, we will find the minimum size of secondary conductor that will be provided short circuit protection by the primary fuse.

To develop the general analysis the extremes of single-phase distribution transformers will be used.

Case 1: 167 kVA Transformer

Figure 6 shows the situation. The smallest cables that can be protected appear to be either 250 kcmil XLP or 350 kcmil THW. These cables have ampacities in conduit or underground of approximately 45-50% of the full load rating of the transformer.

Fig 6

Fig 7

Case 2: 15 kVA Transformer

Figure 7 shows the situation. In this case the cable size is the smallest normally encountered, #6 AWG. The largest transformer fuse that can be used with these conductors appears to be one that would be encountered with a 15-kVA transformer. Fig 6

In this case, the conductors are rated at approximately the full load rating of the transformer. If these same conductors are used with a 25-kVA transformer, they will no longer be protected.

General Conclusions:

If adherence to the NESC is interpreted as limiting conductor fault temperatures to those recommended by IPCEA, then from the examples in this paper the following design goals can be established. While the situations presented were those of single-phase transformers similar problems will arise for secondary conductors on wye grounded secondary of three-phase transformers or where more than three sets of conductors are paralleled to obtain the requisite ampacity.

<u>Medium Voltage Cables:</u>

Conductor and shield protection must consider the thermal characteristics of both the shield and the phase conductors. Otherwise the design may not comply with the NESC.

Fuse selection for the cable will normally be constrained by the shield withstand characteristic.

<u>Low Voltage Cables:</u>

Cables sized for the full load ampacity of the transformer secondary can be provided adequate fault current protection by the primary fuses of the transformers.

Cables rated less than 50% of the rating of the transformer ampacity must be provided fault current protection on the secondary side of the transformer. Protection should be by cable limiters or other fuse type devices. Circuit breakers can be used, as long as fault currents are not so high that, prior to breaker clearing, damage to the insulation occurs.